

UNITED STATES PATENT APPLICATION

**INTEGRATED STACKED MICROCHANNEL HEAT EXCHANGER AND  
HEAT SPREADER**

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## **INTEGRATED STACKED MICROCHANNEL HEAT EXCHANGER AND HEAT SPREADER**

### **Background**

5        Integrated circuits such as microprocessors generate heat when they operate and frequently this heat must be dissipated or removed from the integrated circuit die to prevent overheating. This is particularly true when the microprocessor is used in a notebook computer or other compact device where space is tightly constrained and more traditional die cooling techniques such as direct forced air cooling are  
10      impractical to implement.

One technique for cooling an integrated circuit die is to attach a fluid-filled microchannel heat exchanger to the die. A typical microchannel heat exchanger consists of a silicon substrate in which microchannels have been formed using a subtractive microfabrication process such as deep reactive ion etching or electro-  
15      discharge machining. Typical microchannels are rectangular in cross-section with widths of about 100  $\mu\text{m}$  and depths of between 100-300  $\mu\text{m}$ . Fundamentally the microchannels improve a heat exchanger's coefficient of heat transfer by increasing the conductive surface area in the heat exchanger. Heat conducted into the fluid filling the channels can be removed simply by withdrawing the heated fluid.

20       Typically, the microchannel heat exchanger is part of a closed loop cooling system that uses a pump to cycle a fluid such as water between the microchannel heat exchanger where the fluid absorbs heat from a microprocessor or other integrated circuit die and a remote heat sink where the fluid is cooled. Heat transfer between the microchannel walls and the fluid is greatly improved if sufficient heat  
25      is conducted into the fluid to cause it to vaporize. Such two-phase cooling enhances the efficiency of the microchannel heat exchanger because significant thermal energy above and beyond that which can be simply conducted into the fluid is consumed in overcoming the fluid's latent heat of vaporization. This latent heat is then expelled from the system when the fluid vapor condenses back to liquid form  
30      in the remote heat sink. Water is a particularly useful fluid to use in two-phase

systems because it is cheap, has a high heat (or enthalpy) of vaporization and boils at a temperature that is well suited to cooling integrated circuits.

The heat removal capacity of microchannel heat exchangers can be enhanced by vertically stacking multiple layers of microchannel structures to form a stacked 5 microchannel heat exchanger. Stacked microchannel heat exchangers are more efficient at removing heat from ICs because each additional layer of microchannels doubles the surface area for heat exchange per unit area of the heat exchanger.

Conventionally, heat exchangers are not physically coupled directly to an IC die or package but, rather, are coupled to a metallic heat spreader that is itself 10 coupled to the IC die or package. In the context of mobile computing systems the size of a typical heat exchanger often precludes coupling the heat exchanger directly to the heat spreader thus requiring the addition of a heat pipe or other thermally conductive structure to provide the physical and thermal coupling between the heat exchanger and the heat spreader. Heat pipes or similar devices are bulky and 15 occupy valuable space within a mobile computing system.

#### Brief Description of the Drawings

The foregoing aspects of this invention will become more readily appreciated by reference to the following detailed description, when taken in 20 conjunction with the accompanying drawings, wherein like reference numerals refer to like parts throughout the various views unless otherwise specified. In the drawings:

Figure 1 is a cross-section view of an integrated stacked microchannel heat exchanger and spreader including a stacked microchannel heat exchanger coupled to 25 an integrated circuit (IC) die by a layer of solder in accordance with an embodiment of the invention;

Figure 2 is a cross-section view of an integrated stacked microchannel heat exchanger and heat spreader including a stacked microchannel heat exchanger coupled to an IC die by a layer of solder and a layer of solderable material in 30 accordance with an embodiment of the invention;

Figure 3 is a cross-section view of an integrated stacked microchannel heat exchanger and heat spreader including a stacked microchannel heat exchanger coupled to an IC die by a layer of adhesive in accordance with an embodiment of the invention;

5 Figure 4 is a cross-section view of an integrated stacked microchannel heat exchanger and heat spreader including a stacked microchannel heat exchanger coupled to an IC die using a thermal interface material and fasteners in accordance with an embodiment of the invention;

10 Figure 5 is a block diagram of a mobile computer system employing a closed loop two-phase cooling system including an integrated stacked microchannel heat exchanger and heat spreader in accordance with an embodiment of the invention;

Figure 6 is a schematic diagram of a closed loop cooling system employing an integrated stacked microchannel heat exchanger and heat spreader in accordance with an embodiment of the invention; and

15 Figure 7 is a flow diagram representing implementation of a method for cooling ICs using an integrated stacked microchannel heat exchanger and heat spreader in accordance with an embodiment of the invention.

### Detailed Description

Embodiments of integrated stacked microchannel heat exchanger and spreader apparatus, cooling systems employing the same and methods for cooling electronic components using the same are described. In the following description, 5 numerous specific details such as cooling apparatus and system implementations, types and interrelationships of cooling apparatus and system components, and particular embodiments of integrated stacked microchannel heat exchanger and spreaders are set forth in order to provide a more thorough understanding of the present invention. It will be appreciated, however, by one skilled in the art that 10 embodiments of the invention may be practiced without such specific details or by utilizing, for example, different embodiments of integrated stacked microchannel heat exchanger and spreaders. In other instances, methods for manufacturing integrated stacked microchannel heat exchanger and spreaders or specific mechanical details for implementing cooling apparatus or systems, for example, 15 have not been shown in detail in order not to obscure the embodiments of the invention. Those of ordinary skill in the art, with the included descriptions will be able to implement appropriate functionality without undue experimentation.

References in the specification to one embodiment, an embodiment, an example embodiment, etc., indicate that the embodiment described may include a 20 particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art 25 to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described. Moreover, the particular features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

A number of figures show block diagrams of apparatus and systems 30 comprising integrated stacked microchannel heat exchanger and spreaders, in

accordance with embodiments of the invention. One or more figures show flow diagrams illustrating operations for making or using integrated stacked microchannel heat exchanger and spreaders likewise in accordance with embodiments of the invention. The operations of the flow diagrams will be

5 described with references to the systems/apparatus shown in the block diagrams. However, it should be understood that the operations of the flow diagrams could be performed by embodiments of systems and apparatus other than those discussed with reference to the block diagrams, and embodiments discussed with reference to the systems/apparatus could perform operations different than those discussed with

10 reference to the flow diagrams.

#### Integrated Stacked Microchannel Heat Exchanger and Heat Spreader

To provide effective heat removal, a stacked microchannel heat exchanger is coupled to an IC die or package using an intervening heat spreader to form an

15 integrated heat exchanger and heat spreader. A variety of different types or forms of well-known heat spreaders can be used consistent with the invention, thus, while several embodiments of the invention are described in detail below, other types or forms of heat spreader may be used in combination with a stacked microchannel heat exchanger without departing from the scope or spirit of the invention.

20 Figure 1 illustrates in cross-sectional view one embodiment of an integrated stacked microchannel heat exchanger and heat spreader 100 in accordance with the invention including a stacked microchannel heat exchanger 102 physically and thermally coupled to an IC die 104 by a layer of solder 106. An epoxy underfill 108 is typically employed to strengthen the interface between die 104 and the

25 substrate 110 that die 104 is flip-bonded to by a plurality of solder bumps 112. While the embodiment of Figure 1 illustrates die 104 flip-bonded by a plurality of solder bumps 112, other methods of bonding die 104 to substrate 110 may be used in combination with a stacked microchannel heat exchanger without departing from the scope or spirit of the invention.

Stacked microchannel heat exchanger 102 includes several vertically stacked layers of generally rectangular microchannels 114 having open ends and extending the length of heat exchanger 102. In Figure 1 and the figures that follow the dimensions of microchannels 114 are exaggerated for clarity. The invention is not 5 limited by the number of vertically stacked microchannel layers and the total number of microchannels in heat exchanger 102. The dimensions of microchannels 114, the number of vertically stacked microchannel layers and the total number of microchannels can vary depending on the cooling needs of die 104.

Heat exchanger 102 is one example of a stacked microchannel heat 10 exchanger that may be formed using one of many well-known techniques common to industry practices. For example, single layers of microchannels 114 may be formed in thinned silicon wafers using techniques including but not limited to electro-discharge micromachining, chemical etching and laser ablation. The individual wafers of microchannel-bearing silicon may then be vertically stacked 15 and bonded together to form stacked microchannel heat exchanger 102. In operation, heat exchanger 102 acts as a thermal mass to absorb heat conducted from the integrated circuits within die 104.

In one embodiment die 104 and microchannel heat exchanger 102 are silicon and solder 106 is an interstitial solder such as a low-melting point indium solder for 20 example. In one embodiment solder 106 may initially comprise a solder preform having a pre-formed shape conducive to the particular configuration of the bonding surfaces. The solder preform is placed between the die 104 and heat exchanger 102 during a pre-assembly operation and then heated to a reflow temperature at which 25 point the solder melts. The temperature of the solder and joined components are then lowered until the solder solidifies, thus forming a bond between the joined components.

Figure 2 illustrates in cross-sectional view one embodiment of an integrated stacked microchannel heat exchanger and heat spreader 200 in accordance with the invention including a stacked microchannel heat exchanger 102 physically and

thermally coupled to an IC die 104 by a layer of solder 202 and a layer of solderable material 204.

Generally, solderable material 204 may comprise any material to which the selected solder will bond. Such materials include but are not limited to metals such as copper (Cu), gold (Au), nickel (Ni), aluminum (Al), titanium (Ti), tantalum (Ta), silver (Ag) and Platinum (Pt). In one embodiment, in a process termed backside metallization, the layer of solderable material comprises a base metal over which another metal is formed as a top layer. In another embodiment, the solderable material comprises a noble metal; such materials resist oxidation at solder reflow temperatures, thereby improving the quality of the soldered joints.

Generally, the layer (or layers) of solderable material may be formed over the top surface of the die 104 using one of many well-known techniques common to industry practices. For example, such techniques include but are not limited to sputtering, vapor deposition (chemical and physical), and plating. The formation of the solderable material layer may occur prior to die fabrication (i.e., at the wafer level) or after die fabrication processes are performed. In one embodiment solder 202 may initially comprise a solder preform having a pre-formed shape conducive to the particular configuration of the bonding surfaces.

Figure 3 illustrates in cross-sectional view one embodiment of an integrated stacked microchannel heat exchanger and heat spreader 300 in accordance with the invention including a stacked microchannel heat exchanger 102 physically and thermally coupled to an IC die 104 by a layer of adhesive 302. In one embodiment, heat exchanger 102 and die 104 are both formed from silicon and adhesive 302 is a silicon-to-silicon bonding adhesive such as bisbenzocyclobutene (BCB) for example. BCB and similar polymers provide good heat conduction, are mechanically strong and stable up to temperatures of 300...C. In another embodiment, adhesive 302 is a thermal adhesive. Thermal adhesives, sometimes called thermal epoxies, are a class of adhesives that provide good to excellent conductive heat transfer rates. Typically, a thermal adhesive will employ fine

portions (e.g., granules, slivers, flakes, micronized, etc.) of a metal or ceramic, such as silver or alumina, distributed within in a carrier (the adhesive), such as epoxy.

A further consideration related to the embodiment of Figure 3 is that the stacked microchannel heat exchanger need not comprise a metal. In general, 5 stacked microchannel heat exchanger 102 may be made of any material that provides good conductive heat transfer properties. For example, a ceramic carrier material embedded with metallic pieces in a manner similar to the thermal adhesives discussed above may be employed for the stacked microchannel heat exchanger 102. It is additionally noted that a heat exchanger of similar properties may be 10 employed in the embodiment of Figure 2 if another layer of solderable material is formed over the base of the stacked microchannel heat exchanger 102.

Figure 4 illustrates, in accordance with an embodiment of the invention, an integrated stacked microchannel heat exchanger and heat spreader 400 comprising stacked microchannel heat exchanger 102 coupled thermally to an integrated circuit 15 (IC) die 104 via a Thermal Interface Material (TIM) 402 and coupled operatively to substrate 110 to which the IC die 104 is flip-bonded by a plurality of solder bumps 112. TIM layer 402 serves several purposes; first, it provides a conductive heat transfer path from die 104 to heat exchanger 102 and, second, because TIM layer 402 is very compliant and adheres well to both the die 104 and heat exchanger 102, 20 it acts as a flexible buffer to accommodate physical stress resulting from differences in the coefficients of thermal expansion (CTE) between die 104 and heat exchanger 102.

Stacked microchannel heat exchanger 102 of integrated stacked microchannel heat exchanger and heat spreader 400 is physically coupled to 25 substrate 108 through a plurality of fasteners 404 each one of the plurality of fasteners 404 coupled to a respective one of a plurality of standoffs 406 mounted on substrate 110. The illustrated fasteners 404 and standoffs 406 are just one example of a number of well known assembly techniques that can be used to physically couple heat exchanger 102 to die 104. In another embodiment, for example, heat 30 exchanger 102 is coupled to die 104 using clips mounted on substrate 110 and

extending over heat exchanger 102 in order to press heat exchanger 102 against TIM layer 402 and die 104.

While Figures 1 thru 4 illustrate stacked microchannel heat exchanger 102 thermally and operatively coupled to IC die 104, the invention is not limited in this respect and one of ordinary skill in the art will appreciate that stacked heat exchanger 102 can be thermally and operatively coupled to an IC package containing one or more IC die to form integrated stacked microchannel heat exchanger and heat spreaders while remaining within the scope and spirit of the invention.

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#### Cooling Systems

Figure 5 illustrates one embodiment in accordance with the invention of a mobile computer system 500 having a closed loop two-phase cooling system 502 including an integrated stacked microchannel heat exchanger and spreader (not shown) coupled thermally and operatively to an integrated circuit (IC) die or package 504. System 500 includes a bus 506, which in an embodiment, may be a Peripheral Component Interface (PCI) bus, linking die or package 504 to a network interface 508 and an antenna 510. Network interface 508 provides an interface between IC die 504 and communications entering or leaving system 500 via antenna 510. The stacked microchannel heat exchanger within cooling system 502 acts as a thermal mass to absorb thermal energy from, and thereby cool, die or package 504. Cooling system 502 is described in more detail below with respect to Figure 6. While the embodiment of system 500 is a mobile computer system, the invention is not limited in this respect and other embodiments of systems incorporating cooling systems utilizing integrated stacked microchannel heat exchanger and spreaders in accordance with the invention include, for example, desktop computer systems, server computer systems and computer gaming consoles to name only a few possibilities.

Figure 6 illustrates one embodiment in accordance with the invention of a closed loop two-phase cooling system 502 having a stacked microchannel heat

exchanger 102 coupled thermally and operatively to an integrated circuit (IC) die (not shown). System 502 further includes a heat rejecter°600 and a pump°602. System 502 takes advantage of the fact, as discussed earlier, that a fluid undergoing a phase transition from a liquid state to a vapor state absorbs a significant amount of 5 energy, known as latent heat, or heat of vaporization. This absorbed heat having been converted into potential energy in the form of the fluid s vapor state can be subsequently removed from the fluid by returning the vapor phase back to liquid. The stacked microchannels, which typically have hydraulic diameters on the order of hundred-micrometers, are very effective for facilitating the phase transfer from 10 liquid to vapor.

System 502 functions as follows. As the die circuitry generates heat, the heat is conducted into stacked microchannel heat exchanger 102. The heat increases the temperature of the thermal mass represented by heat exchanger 102, thereby heating the temperature of the walls in the stacked microchannels. Liquid is pushed 15 by pump°602 into an inlet port°604, where it enters the inlet ends of the stacked microchannels. As the liquid passes through the stacked microchannels, further heat transfer takes place between the microchannel walls and the liquid. Under a properly configured heat exchanger, a portion of the fluid exits the stacked microchannels as vapor at an outlet port°606. The vapor then enters heat 20 rejecter°600. The heat rejecter comprises a second heat exchanger that performs the reverse phase transformation as stacked microchannel heat exchanger°102 — that is, it converts the vapor entering at an inlet end back to a liquid at the outlet of the heat rejecter. The liquid is then received at an inlet side of pump°602, thus completing the cooling cycle.

25 Generally, the pump 602 used in the closed loop cooling system 502 employing integrated stacked microchannel heat exchanger and heat spreaders in accordance with the embodiments described herein may comprise electromechanical (e.g., MEMS-based) or electro-osmotic pumps (also referred to as "electric kinetic" or "E-K" pumps). Electro-osmotic pumps are advantageous over electromechanical 30 pumps because they do not have any moving parts and hence are more reliable than

electromechanical pumps. Since both of these pump technologies are known in the microfluidic arts, further details are not provided herein.

In this manner system 502 acts to transfer the heat rejection process from the IC die or package, which, for example, is typically somewhat centrally located 5 within the chassis of a notebook computer to the location of the heat rejecter heat exchanger, which can be located anywhere within the chassis, or even externally.

Figure 7 illustrates a flow diagram representing implementation of a method for cooling ICs using an integrated stacked microchannel heat exchanger and heat spreader in accordance with an embodiment of the invention. In the embodiment of 10 figure 7 the ICs being cooled include a processor IC and can include additional components such as platform chipset ICs, memory ICs, video ICs, co-processors or other ICs. Some or all of the additional ICs can be spatially separated from the processor IC or can be included in an IC package along with processor IC. In block 702, at least one stacked microchannel heat exchanger such as heat exchanger 102 is 15 thermally coupled to a least one IC. In block 704, a working fluid such as water is passed through the stacked microchannel heat exchanger. At block 706, heat is transferred from the IC into working fluid within the stacked microchannel heat exchanger thereby converting a portion of the working fluid from liquid to vapor phase. Finally, at block 708, the working fluid exiting the stacked microchannel 20 heat exchanger is passed through a heat rejector where heat is removed from the working fluid converting the working fluid back to a liquid phase.

Thus, methods, apparatuses and systems of integrated stacked microchannel heat exchanger and heat spreaders have been described. Although the invention has been described with reference to specific exemplary embodiments, it will be evident 25 that various modifications and changes may be made to these embodiments without departing from the broader spirit and scope of the invention. For example, while the method, apparatuses and systems for utilizing integrated stacked microchannel heat exchanger and heat spreaders are described in reference to the invention's use in a two-phase liquid cooling system, in other embodiments, such method and systems

are applicable to use in a single-phase cooling system. Therefore, the specification and drawings are to be regarded in an illustrative rather than a restrictive sense.